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HALL EFFECT IN MULTILAYERS BASED ON Pd AND Fe

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The paper presents results of experimental investigations of singularities of the Hall effect in multilayers based on Pd *and* Fe*. It is shown that the value of the Hall coefficient depends on the total thickness of the multilayer (the number of fragments), the thickness of nonmagnetic layer, and the annealing temperature range of the studied film samples. A satisfactory agreement between the experimental and calculated data based on the model of parallel connection of individual fragments of a multilayer is obtained.*

Keywords: *GALVANOMAGNETIC EFFECTS, MULTILAYER BASED ON* Fe *AND* Pd*, SIZE EFFECTS, HALL EFFECT, ANNEALING TEMPERATURE.*

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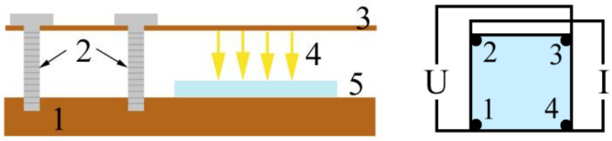
1. INTRODUCTION

Galvanomagnetic effects (GME) are the set of phenomena connected with the magnetic field action on the electrical properties of conductors with current. Transverse GME when magnetic field is directed perpendicular to the electric current direction are substantially expressed. The Hall effect (appearance of the potential difference (the Hall electromotive force)) along the direction perpendicular to the field) and the transverse magnetoresistive effect (change of the conductor electrical resistance under the magnetic field action) are among them. The Hall electromotive force in ferromagnetic films is determined by the magnetization behavior [1], and the less film thickness, the more magnetization value. In connection with the development of nanoelectronics and spintronics, study of the Hall effect is under great attention, since high sensitive meters of magnetic field, microelectronic compasses, displacement and rotation frequency sensors [2, 3] can be produced based on this effect. Analysis of anisotropic processes on the ferromagnetic/antiferromagnetic interfaces [4] and study of remagnetization processes in spin-valve structures [5] can be also performed using the Hall effect. Recently, development and application of the Hall effect investigation techniques in multilayer film systems, the results of which are successfully used for the determination of the charge carrier concentration and mobility, arouse a great interest. Ammeters for electrical current measurement up to 100 kA, meters of linear and angular displacements, measurement devices for magnetic field gradient and magnetic flux, non-contact transducers of continuous current into alternating one, recording and reproducing heads [6] are produced based on the Hall sensors.

Considerable information concerning structural and magnetic properties of two-component film materials based on Pd and Fe which can be used as the components of sensitive elements of the mentioned sensors is currently obtained, though question about the features of the Hall effect (HE) in multilayers based on these metals is still unstudied that is defined the aim of the present work.

2. EXPERIMENTAL INVESTIGATION TECHNIQUES

Multilayers based on Pd and Fe were obtained as a result of layer-by-layer condensation by the thermal evaporation method using ultra-high vacuum plant (pressure of the residual atmosphere is 10^{-7} Pa), high vacuum chamber based on turbomolecular pump for the annealing of film samples. Effective thickness was controlled by the quartz resonator method based on the measuring system consisting of three quartz plates: the main (gage) one and two additional (measuring). Measurement of the HE was carried out at the room temperature by the four-probe scheme (Fig. 1). Thickness of Pd layers was equal to 0,4; 0,6; 0,9; 1,1; and 1,4 nm, and of Fe layers – 0,6 or 0,9 nm.



a b

Fig. 1 *– Four-probe scheme for the HE investigation (a) and scheme for measuring of the output voltage (b): 1 – copper plate which provides a heat sink; 2 – hold-down screws; 3 – flexible textolite plate; 4 – contacts; 5 – sample*

When measuring the Hall electromotive force (EMF) in the case of the perpendicular direction of electric current and magnetic field, contribution of additional (parasitic) EMF which appear in the scheme due to side thermo- and galvanomagnetic effects (Fig. 1b) was taken into account. To decrease the influence of these negative factors and non-symmetry of the arrangement of contacts, we have performed four measurements at different directions of electric current through the contacts 2-4, 4-2, and 1-3, 3-1 in the magnetic field presence. Directions of electric current I and magnetic field induction B were mutually perpendicular. Step of the magnetic field induction was equal to 0,001 T.

Value of the Hall constant R_H was determined from the relation

$$R_H = U_H d/(IB),$$

where U_H is the Hall voltage; I is the electric current; B is the magnetic induction; d is the sample thickness.

The authors have used the Van-der-Pauw [6] method to measure the resistivity (ρ) and Hall constant R_H for film samples of an arbitrary geometry. Application of the mentioned method is possible under fulfillment of the following conditions: contacts pads with minimal geometric sizes are placed on the edges (periphery) of multilayer; thin film sample can be continuous and uniform in thickness all over the substrate.

Thermal treatment of multilayers was performed in a special device whose scheme is shown in Fig. 2. Measurement of the resistance was carried out by multimeter NP 34410A with the accuracy of 0,0015%. For the temperature control we have used chromel-alumel thermocouple (precision is ± 1 K), and its indications were registered by multimeter Escort EDM3150. Measurement was performed during three stabilized cycles in automated mode by the scheme "heating ↔ cooling" at constant velocity of 2-3 K/min.

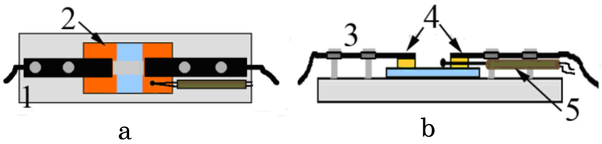


Fig. 2 *– Scheme of the device for thermal treatment of multilayers (a – top view; b – lateral view): 1 – substrate-table; 2 – sample; 3 – screws for fastening of pressure contacts 4; 5 – thermocouple*

Electron-microscope investigations indicate that separate layers which are part of multilayer consist of islands which adjoin to each other that provides electrical conduction of the system in whole. From this point of view, each two-layer fragment of multilayers represents a quasi-biplate.

3. EXPERIMENTAL RESULTS

In the work we present the results of the experimental investigations of the HE features in multilayers based on Pd and Fe. As known (see, for example, [7]), the value of R_H of metals depends on the band structure and shape of the Fermi surface. Interfaces of different layers significantly influence the value of R_H. Moreover, we have to note that both the external and internal magnetic fields act on conduction electrons in ferromagnetic layers that conditions the so-called usual and anomalous HE. In the region of intrinsic conductivity sign of the Hall EMF corresponds to the sign of the carriers, whose mobility is larger. If experimental measurements show the negative value of the Hall voltage, this implies the advantage of the electron conduction in multilayer. Further, we will call the value of R_H without sign "–".

In Fig. 3 we present the generalized field dependences $U_{\mathrm{H}}(B)$ for the un-annealed (T = 300 K) $[Pd(1,1)/Fe(0,9)]_3/S$ and $[Pd(1,1)/Fe(0,9)]_5/S$ multilayers which were thermally treated in the temperature ranges of ΔT_1 = 300-460 K, ΔT_2 = 300-680 K, and ΔT_3 = 300-790 K. As seen from Fig. 3, broadening of the range of thermal annealing of the samples from 300 to 790 K leads to the decrease in the Hall voltage at B = 1 T from 1,0 to 0,4 mV. Comparative analysis of Fig. 3a and Fig. 3b shows that with the increase in the total thickness from 6 to 10 nm (number of fragments from 3 to 5), the value of the Hall voltage decreases by 1,5-2 times.

For the ranges of thermal treatment ΔT_1, ΔT_2, and ΔT_3, curves $U_H(B)$ have different slope angles that displays phase transformations in the film: at T = 680 K individuality of Pd and Fe layers disappears, and film alloy with the disordered structure is formed (Fig. 3a); at T = 790 K hysteresis of the curve takes place, and it implies the formation of the ordered $L1_0$ phase and presence of the perpendicular component of magnetization in the film sample (Fig. 3b).

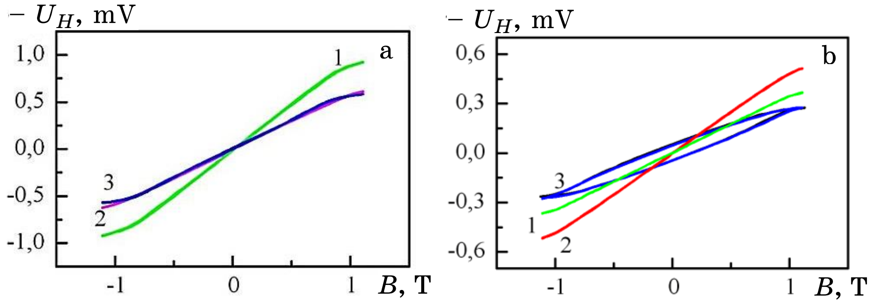


Fig. 3 *– Field dependence of the Hall voltage for [Pd(1,1)/Fe(0,9)]$_3$/S (a) and [Pd(1,1)/Fe(0,9)]$_5$/S (b) film systems which are unannealed (1) and after thermal treatment to* 680 *K (2) and* 790 *K (3)*

The value of the voltage U_H in multilayers depends not only on the thermal treatment range and number of fragments, but also on the thickness of non-magnetic layer, in the given case Pd (Fig. 4). Thus, in [Pd(x)/Fe(0,6)]$_{10}$/S multilayers varying Pd layer thickness from 0,4 to 1,4 nm, maximum value of the Hall voltage corresponds to the thickness of d_{Pd} = 0,6 nm, i.e. in the case when $d_{Pd} = d_{Fe}$, minimum value of the Hall voltage is observed at the thickness of d_{Pd} = 1,4 nm, when $d_{Pd} > d_{Fe}$.

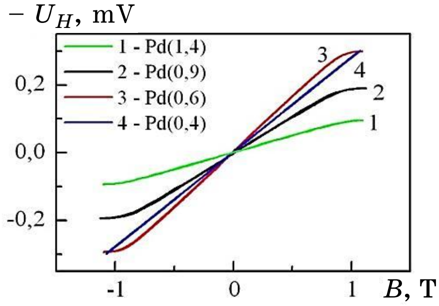


Fig. 4 *– Dependence of the Hall voltage on the thickness of [Pd(x)/Fe(*0,6*)]$_{10}$/S intermediate layer of the film sample at T =* 300 *K*

To calculate the value of R_H we use the theoretical model for the HE of two-layer Ni/Cu and Ta/Cu films which was proposed by the authors of [8], where two-layer film (in our case, this is the fragment of the multilayer) is considered as the parallel connection of separate layers. According to [8], the value of R_H is expressed by the following correlation:

$$R_H = (d_1 + d_2) \cdot \left(\frac{R_{H1}\rho_2^2 d_1 + R_{H1}\rho_1^2 d_2}{(\rho_2 d_1 + \rho_1 d_2)^2} \right),$$

where R_{H1} and R_{H2}, d_1 and d_2, ρ_1 and ρ_2 are, respectively, the Hall constants for materials of the 1-st and 2-nd layers, layer thicknesses, and conductivity of separate layers which corresponds to the thicknesses d_1 and d_2.

The comparison results of the theoretical and calculated data are given in Table 1. The data of Table 1 shows that size dependence is typical for the HE, in particular, at total thickness of multilayer from 10 to 20 nm, the value of R_H decreases from $4{,}84 \cdot 10^{-9}$ to $3{,}69 \cdot 10^{-9}$ m^3/C.

Table 1 *– Comparison of the experimental and calculated data for the Hall constant of Pd/Fe multilayers*

Sample	$R_H^{exp}\cdot10^9$, m^3/C	$R_H^{cal}\cdot10^9$, m^3/C	$(R_H^{cal}-R_H^{exp})/R_H^{exp}$, %
$[Pd(0,4)/Fe(0,6)]_{10}/S$	4,80	3,23	33
$[Pd(0,6)/Fe(0,6)]_{10}/S$	4,84	2,65	45
$[Pd(0,9)/Fe(0,6)]_{10}/S$	4,24	2,12	50
$[Pd(1,4)/Fe(0,6)]_{10}/S$	3,69	1,65	55
$[Pd(1,1)/Fe(0,9)]_3/S$	5,49	2,38	57
$[Pd(1,1)/Fe(0,9)]_5/S$	5,07	2,38	53
$[Pd(1,1)/Fe(0,9)]_{10}/S$	3,97	2,38	40
$[Pd(1,4)/Fe(0,9)]_{10}/S$	3,77	2,08	45
Pd(3)/Fe(3)/Pd(6)/Fe(20)/S	0,97	0,20	29
Pd(5,7)/Fe(4,3)/S	1,62	2,28	– 40

The aforesaid theoretical model does not take into account the processes of electron scattering at the interfaces of separate layers which, as known [9, 10], significantly influence the electrophysical and galvanomagnetic properties of the films. Divergence of the experimental and calculated values of the Hall constant (Fig. 5a) is explained by the influence of electron scattering at the interfaces, though many details of this process are still misunderstood. In particular, the reason of the decrease in the value of R_H^{exp} (Fig. 5a) with the increase in the number of fragments, and, consequently, number of interfaces that can condition the same values of R_H^{cal} and R_H^{exp} during extrapolation of N (dependences in Fig. 5a will converge to point) is unknown. The reason of the divergence of the experimental and calculated dependences in Fig. 5b is also misunderstood, and it is not quite clear why aren't they extrapolated at $d_{Pd} \to 0$ on the corresponding value of R_H (d_{Fe} = 0,9 nm), and at $d_{Pd} \to \infty$ – on the value of R_H for bulk Pd.

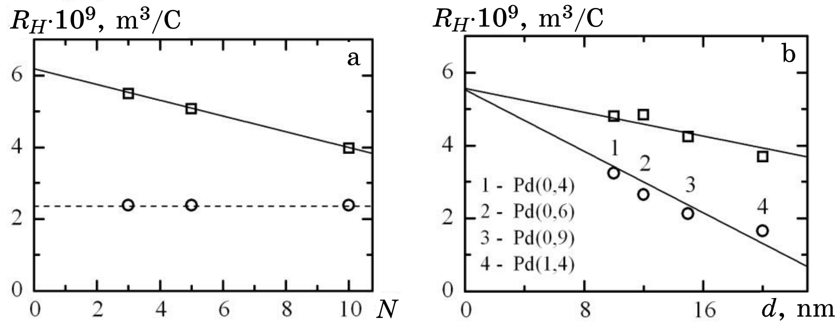


Fig. 5 *– Dependence of the Hall constant on the number of fragments for [Pd(1,1)/Fe(0,9)]$_N$/S film system (a) and total thickness of [Pd(x)/Fe(0,6)]$_{10}$/S film system (b): □ – experimental and ○ – calculated results*

As seen from the data in Table 1, depending on the number of fragments and total thickness of multilayer, contribution of the processes of electron scattering is from 33 to 55% (multilayers with the number of fragments of N = 10); 53-57% (N = 3, 5), and from 29 to 40% for two- and four-layer films with an arbitrary thickness of separate layers.

4. CONCLUSIONS

On the ground of the results of the experimental investigations of the HE in multilayers based on Pd and Fe, we can conclude the following:

HE possesses the size and temperature dependences. The value of the Hall constant depends on some factors: number of fragments, total thickness of multilayer, thickness of Pd layer, and annealing range of the studied film samples. The maximum HE for $[Pd(0,6)/Fe(0,6)/S]_N$ multilayers is observed in the case when $d_{Fe} = d_{Pd} = 0{,}6$ nm.

We have obtained a satisfactory fit of the experimental and calculated data based on which it is possible to evaluate contribution of the processes of electron scattering at the interfaces into HE. It is shown that depending on the number of fragments and total thickness of the sample, contribution of the scattering processes is from 30 to 57%.

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